Chapter 8 Protecting Infrastructure: Costs and Impacts

Contributing Authors: Katie McDowell Peek, Courtney Schupp, and Amanda Babson

Infrastructure Adaptation

This chapter identifies ultiple strategies and associated costs for protection and adaptation of infrastructure in the coastal zone. While this chapter focuses specificall on infrastructure, many of these adaptation strategies can also be applied to archeological resources and other cultural resources; for a more detailed discussion of relevant issues, see “Chapter 5 Cultural Resources.”

Infrastructure comprises the physical assets and components of a region that provide service to the public, and includes buildings, roads, water and wastewater systems, bridges, and electrical grids. Some of these park assets are also protected cultural resources. The National Park Service manages numerous types of coastal infrastructure that will be affected by climate change and is investigating coastal infrastructure adaptation options at park, regional, and servicewide levels. As coastal vulnerability increases with changes in the climate, public pressure will also increase to armor the coastline.

Climate change adaptation is important for National Park Service (NPS) assets in terms of both planning new construction, such as ensuring that the location is not along an eroding shoreline or within a flood zone, and managing existing assets through engineered protection, relocation, or abandonment. Adaptation efforts must consider the NPS mission and the balance of natural, historic, and cultural resources, as well as recreational access, budget constraints, and public and political pressure.

This chapter describes different climate change adaptation options for infrastructure within coastal parks, with emphasis on sea level rise and storms. Options include hard stabilization structures, relocation and retreat, redesign, abandonment, and creation of nature-based features (Bridges et al. 2015), such as beach nourishment and living shorelines. A continuum of these options from hard to soft or nature-based options is described by SAGE, NOAA, and USACE (2014) and illustrated in figu e 8.1; their costs, benefits, a d impacts are summarized in table 8.1. Online resources will be updated to supplement this document and can be found at http://www.nps.gov/subjects/climatechange/coastalhandbook.htm.

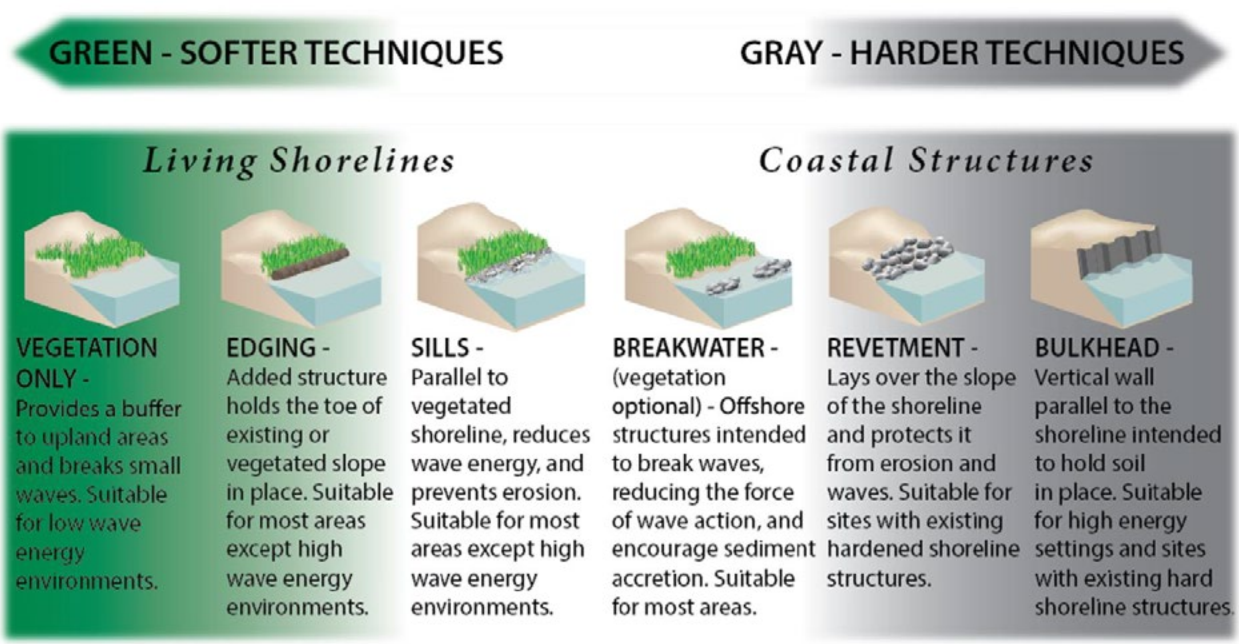


Figure 8.1. A continuum of green (soft) to gray (hard) shoreline stabilization techniques. Figure 1 from NOAA (2015) based on SAGE, NOAA, and USACE (2014).

Table 8.1. Summary of adaptation options and their costs, benefits, and impacts.

Adaptation Option	General Cost	Benefits	Disadvantages/Impacts
Onshore, Shore-Parallel Structures	$2,000 – $3,000/ft ($6562-$9843/m)	Reduce upland erosion	Disrupts natural processes; causes erosion; impacts habitat
Shore-Perpendicular Structures	Groins: $250 – $6,500/ft ($820-$21,325/m) Jetties: $16,000/ft ($52,493/m)	Groins: Widen beach Jetties: Limit sediment flow and wave energy in inlet	Disrupt natural processes (longshore transport); cause downdrift erosion; cascading effect of installation (groins); hinder inlet migration (jetties)
Breakwaters	Initial: $16,000/ft ($52,493/m) Annual maintenance: over $500/ft ($1640/m)	Reduce force and height of waves; allow accretion landward of structure	Navigation hazard; disrupt natural processes; cause downdrift erosion; no high water protection
Beach Nourishment	$300 – $1,000 ft ($984-$3,281/m) per linear foot or between $5 and $30 ($3.80 and $23 per cubic meter) per cubic yard of sand	Increase beach sand volume/ width; reduce wave energy near infrastructure; protection from moderate water rise; can promote tourism, rapid visible change	Temporary solution; does not reduce or eliminate erosion; sand compatibility limitations; impacts on wildlife on beach and at borrow sites; disrupts natural beach processes; can encourage increased development in high-risk areas
Sand Fencing	Inexpensive	Support natural vegetation growth (and sand accumulation); reduce wind stress and salt spray	Can create debris and safety hazards when destroyed
Living Shorelines	Initial: $1,000 ft ($3,281/m) Annual maintenance: $100/ft ($328/m)	Provide habitat; dissipate wave energy; slow inland water transfer	No upland flood protection; vegetation survival can be limited; hybrid techniques that include hard structures disrupt sediment processes
Redesign the Structure	May be lower than complete removal or relocation; adaptive maintenance costs can increase with redesign	Prolong accessibility; postpone need to find new site for structure; allow historical structure to remain in associated landscape	Pilings can be undermined by erosion or affected by groundwater; means of access may change
Relocate	$800 – $40,000/ft ($2625-$131,234/m)	Long-term solution, reduced maintenance needs; allow natural processes	Lack of appropriate relocation site; loss of historical context; size limitations
Abandon in Place	Reduced short-term maintenance costs	Reduced maintenance needs; can eliminate need for protective structures	Deterioration over time; attractive nuisance; loss of historical value; potential for introduction of hazardous materials

Protect in Place: Costs, Benefits, and Impacts of Infrastructure Adaptation Options

Many adaptation efforts have focused on protecting infrastructure in place by stabilizing the shoreline using seawalls, groins, bulkheads, and soft stabilization techniques, such as beach nourishment. These are strategies to resist change that are often not long-term solutions because climate change and sea level rise will continue to threaten the assets, and the stabilizing structures will require ongoing maintenance and repair.

Hard stabilization structures can have adverse impacts, which are described within each section below; there are also impacts common to all of them. By changing natural shoreline processes in the project area, the structures may reduce sediment transport to downdrift areas, which may also have natural and cultural resources to be considered. If downdrift erosion needs to be mitigated, there will be additional costs for stabilization or nourishment. As sea level rises and erosion continues, the shoreline may migrate away from the fi ed structure, requiring rehabilitation and extension to re-attach the structure to land. Also, hard stabilization and beach nourishment can give the false sense of security and reduced risk in an area. Although well intentioned, these projects could induce more risk by encouraging development within these vulnerable areas.

Hard stabilization often impacts wildlife habitat and ecosystem services and may also limit the extent of or seriously degrade seagrass, salt marsh, and coral reefs, all of which in themselves attenuate waves and provide a level of coastal protection and other ecosystem services, and all of which must be protected under NPS policies and regulations. Some studies have found that adding hard structures increases species diversity, particularly if the surface is complex (rough and pitted instead of smooth) (Moschella et al. 2005; Chapman and Underwood 2011). Structures diversify habitat through new substrate types and differences in wave energy levels seaward and landward of structures (Martin et al. 2005). Compared to hard bottom habitat, breakwaters can show lower overall species richness than rocky shores because they are less established, and they have less habitat complexity and spatial extent (Moschella et al. 2005) although some studies have shown no significa t difference (Pister 2009). Some studies indicate that anthropogenic structures favor invasive or exotic species over native ones (Wasson, Fenn, and Pearse 2005; Glasby et al. 2007; Tyrrell and Byers 2007). These changes to the local coastal ecosystem are substantial and may not be desirable in the context of conservation and park values.

As detailed in "Chapter 2 Policy," NPS policy has been to allow natural shoreline processes to continue and to investigate mitigation options for the effects of human alterations to shoreline processes (NPS Management Policies 2006 § 4.8.1.1). Any such intervention must be kept to the minimum necessary to achieve the stated management objectives (NPS Management Policies 2006 § 4.1 and § 4.8.1.1). A thorough decision-making process related to emplacing new structures will include evaluations of what happens when decisions must be made to repair, replace, or remove the structures (Nordstrom 2014).

The following section describes the costs, benefits, and impacts of protecting assets in place using various coastal engineering approaches. A review of many coastal stabilization structures can be found in Nordstrom (2014).

Onshore, Shore-Parallel Structures: Seawalls, Revetments, and Bulkheads

Seawalls (figu e 8.2) are onshore, shore-parallel structures built along open coasts with the primary purpose of protecting the resource behind the seawall from wave action. They are commonly constructed with a vertical, stepped, or curved face using stone, steel, concrete, or wood (Benoit et al. 2007).

Revetments are placed directly on an existing slope, embankment, or dike to protect the upslope area from waves and strong currents, sometimes at the expense of the downslope area. They are commonly built to preserve the existing uses of the shoreline and to protect the slope. Like seawalls, revetments armor and protect the land and structure behind them. Revetments are commonly constructed using armorstone (in high wave energy environments), articulated concrete mattress (on riverbanks and in low and intermediate wave environments) (Leidersdorf, Gadd, and McDougal 1989), or rip-rap stone (in lower wave energy environments) in combination with smaller stone and geotextile fabrics. Other construction materials include gabions, placed concrete (usually in stepped fashion), pre-cast concrete blocks, and grout-filled bags

Figure 8.2. A seawall protects Fort Warren on Georges Island at Boston Harbor Islands National Recreation Area. Photograph by NPS.

Bulkheads (figu e 8.3) are vertical structures or partitions, usually running parallel to the shoreline on sheltered coasts, for the purpose of retaining upland soils while providing protection from wave action and erosion. Bulkheads are commonly rock-filled timber cribs a d gabions, steel/composite sheet pile, concrete blocks, or armorstone units (Coburn, Griffith, and Young 2010). They can be freestanding or can have a series of tiebacks for stability (Benoit et al. 2007).

Sea level rise and increased wave heights may necessitate increased maintenance or elevation of the hard structures to maintain their effica . Increased wave heights and scour at the base of the structure are likely to reduce structure stability (NRC 2014). Seawalls are effective against coastal floodi g only if they prevent tides from fi tering up through the ground and can compound problems when they prevent rainwater from draining out (Spanger-Siegfried, Fitzpatrick, and Dahl 2014). As sea level rises, the beach in front of the structures will be submerged, resulting in a loss of recreation opportunities and habitat (Heberger et al. 2009).

Costs

The construction costs for shore-parallel engineering structures vary widely depending on factors such as material, height, land characteristics, and location. Total planning and installation is commonly around $2,000 to $3,000 per linear ft ($6,500 to $9,800 per m) but has topped $10,000 per linear ft ($32,800 per m) in several projects. Repair and replacement of deteriorating seawalls, revetments, and bulkheads can be more expensive than new construction. Examples from within and outside the National Park Service are compiled here.

1. **Montauk Lighthouse, New York: Seawall and Stone Revetment Construction (2006)**
   The US Army Corps of Engineers (USACE) constructed a stone seawall and revetment in 2006 around a portion of the Montauk Lighthouse, part of the Montauk Point State Park in New York. The project was labeled as a "hurricane and storm damage reduction project" and total construction costs were estimated by the USACE as $13,720,000 for 840 linear ft (256 m) at 40 ft [12 m] wide, and 25 ft [7.6 m] above National Geodetic Vertical Datum of 1929). This seawall and revetment replaced a deteriorated seawall installed in the 1940s (USACE 2005).
   Approximate cost: $16,665/ft ($54,675/m)
2. **Harkers Island, Cape Lookout National Seashore: Bulkhead Repairs and Replacement (2007)**
   The bulkhead at the headquarters of Cape Lookout National Seashore on Harkers Island was repaired and replaced starting in 2007. The work included the construction of a vinyl sheet pile bulkhead along more than 740 ft (225 m) of shoreline and boat ramp repair, with an award value of $2,042,372 (USACE 2007).
   Approximate cost: $2,759/ft ($9,052/m)
3. **Ellis Island, New York: Seawall Repair (2010)**
   Major repair of the Ellis Island seawall began in 2010. Ellis Island is situated within the Hudson River in New York and is part of the Statue of Liberty National Monument. Approximately 5,550 linear ft (1,690 m) of deteriorating seawall was repaired at an estimated cost of $20.9 million (US DOI 2010).
   Approximate cost: $3,800/ft ($12,470/m)

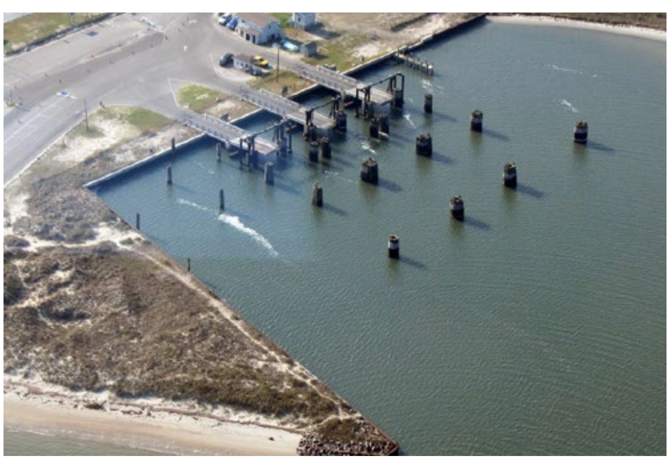


Figure 8.3A. Bulkheads at the Hatteras Island ferry landing on Ocracoke Island, NC. Photograph by NPS.

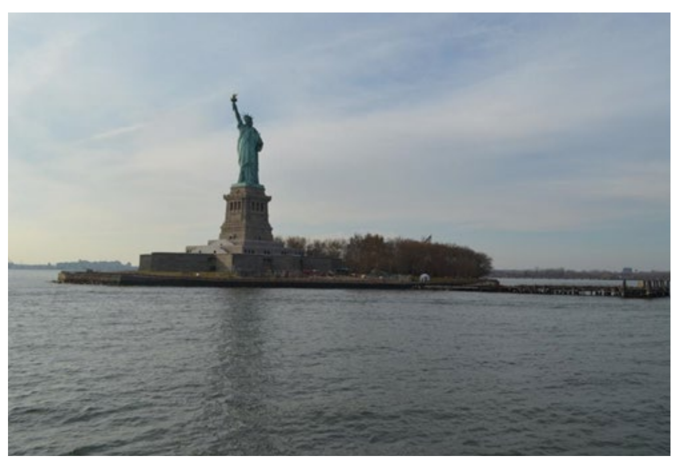


Figure 8.3B. Bulkheads protect Liberty Island. Photograph by NPS.

4. **Thomas Jefferson Memorial, Washington, DC: Seawall Repair and Replacement (2011)**
   A replacement of the seawall along the Potomac River at the Thomas Jefferson Memorial in Washington DC was completed in 2011. The work was done by Clark Construction for the National Park Service at a cost of approximately $13 million. This project required the removal of 500 linear ft (152 m) of old seawall and complete replacement with new piling and seawall (NPS 2014b).
   Approximate cost: $26,000/ft ($85,526/m)
5. **Scituate Lighthouse, Massachusetts: Rock Revetment Improvement and Repair (2014)**
   Repairs to the granite revetment around Scituate Lighthouse in Massachusetts included replacing around 400 linear ft (122 m) of the revetment with new granite boulders at a cost of $800,000 (Shields 2013).
   Approximate cost: $2,000/ft ($6,562/m)
6. **Marshfield, Massachusetts: Seawall Replacement (2013)**
   The oceanfront seawall in Marshfi ld, Massachusetts, was reconstructed in 2013 at a cost of $3.2 million to repair 1,131 linear ft (345 m) of the concrete and stone seawall with a height increase of 2 ft (0.6 m) (Trufant 2013). In January 2014, winter storms destroyed sections of the seawall, and a 1,000 ft (305 m) section, which is less than half of the damaged length, was reconstructed with a 2 ft (0.6 m) height increase in the fall of 2015 at a cost of $4 million (Conti 2015).
   Approximate cost: $3,379/ft ($11,076/m)
7. **Elliot Bay, Seattle, Washington: Seawall Replacement (2013)**
   The Elliot Bay seawall is currently being replaced in Seattle, Washington, from South Washington Street to Broad Street (approximately 4,000 ft [1,220 m]). The cost of the replacement has been estimated at $300 million (Thompson 2012).
   Approximate cost: $75,000/ft ($246,063/m)
8. **Mantoloking and Brick Township, New Jersey: Stone Seawall Construction (planned)**
   A new steel seawall is being planned along the oceanfront in the communities of Mantoloking and Brick Township. It will extend for 10,636 ft (3,242 m) and has a cost estimate of $78,905,000, including purchase of easements and property (USACE 2015).
   Approximate cost: $7,418/ft ($24,338/m)
9. **Riis Landing, Gateway National Recreation Area: Bulkhead Repair (2013)**
   An award was made with a construction company to make repairs to the bulkhead at Riis Landing in the Jamaica Bay unit of the Gateway National Recreation Area at a cost of $1.1 million; the bulkhead is approximately 500 ft (152 m) in total length (NPS 2012).
   Approximate cost: $2,200/ft ($7,217/m)

Benefits

Seawalls, revetments, and bulkheads reduce the impact of wave energy and associated erosion on coastal assets directly behind them along vulnerable shorelines. These structures may be a good choice for protecting assets that are not feasible to relocate, such as cultural landscapes and associated sensitive cultural and historic assets.

Impacts and Disadvantages

These structures are expensive and disturb the natural sediment transport processes that allow a beach to maintain itself. They cause both active and passive erosion of the beach in front of the structure. When waves hit a seawall or bulkhead, they are reflec ed downward, increasing scouring at the toe of the wall (active erosion). This impedes the natural landward migration of beaches in response to sea level rise (passive erosion). The reflec ed wave energy also degrades seagrass, submerged habitat, and marsh areas that might otherwise grow on the bay side of structures (Titus and Strange 2008). If a bulkhead is constructed at the shoreline, the area landward of a bulkhead is typically filled, co verting existing marsh or beach to uplands (Benoit et al. 2007); this can be considered an impact to existing habitat but a benefit to uplands. Structures made of rip-rap stone have an additional disadvantage: they are very diffi lt to clean following an oil spill, because oil becomes entrained within the structure and is then slowly released over a much longer time scale than it might otherwise be.

All three structure types provide only a temporary solution to a threatened asset. The beach that is seaward of the structure will narrow and steepen as soon as the structure is constructed. Stone or riprap is often placed at the toe of a bulkhead to absorb some of the wave energy (Benoit et al. 2007). Over time the scouring at the toe of the structure will cause destruction of the beach ecosystem, including turtle and bird habitat, and can remove the public recreational beach. Recurring beach nourishment is often needed when seawalls are placed on the oceanfront to replace the beach that will eventually be lost seaward of the structure. It is generally recognized that seawalls, revetments, and bulkheads can also cause “end effect” erosion, which occurs when the structure causes erosion on the down-drift side of the structure. The structures need to be maintained and repaired (at a high cost) and are often overtopped and damaged by water during storms. It is possible to design seawalls to withstand some overtopping so that following a storm, they can return to service quickly.

An additional limitation of seawalls is the incorrect perception that they are designed to prevent floodi g, even when their height is insuffi ent and their intended purpose is to prevent erosion. This is a kind of induced risk, in that the risk reduction measure can lead to increased overall risk, such as residents’ failure to evacuate during dangerous conditions or leaving resources vulnerable to floodi g due to a misperception that the structure can protect them.

Shore-Perpendicular Structures: Jetties and Groins

Jetties (figu e 8.4) are hard structures that extend perpendicularly or at nearly right angles from the shore and are commonly used to limit the volume of sediment deposited in inlet channels, prevent inlet migration, and decrease wave energy around inlets.

Groins (figu e 8.5) are structures that extend perpendicularly or at nearly right angles from the shore and are shorter than jetties (Coburn, Griffith, and Young 2010). Often constructed in groups called groin fi lds, their primary purpose is to trap and retain sand that is being transported alongshore to build the beach on the updrift side of the structure. Jetties and groins can be constructed from a wide range of materials, including armorstone, pre-cast concrete units or blocks, rock-filled timber cribs a d gabions, steel sheet pile, timber sheet pile, and grout filled bags and tubes.

Sea level rise increases the possibility of flan ing or submergence of these structures (Heberger et al. 2009). Flanking may occur during high tides, because landward retreat of the beach and dune line leave the structure’s landward attachment point exposed. Submergence of the structure can lead to overtopping by the longshore current (Heberger et al. 2009).

<u>Costs</u>

The cost of groin construction, repair, and replacement generally ranges from $250 to $6,500 per linear ft ($820 to $21,325 per m) depending on the material used (NCCRC 2010). Jetties tend to be more expensive, reaching up to $16,000 per linear ft ($52,495 per m). Jetties require maintenance, such as elevating the jetty height and extending the downdrift jetty inland

Figure 8.4. Ocean City Inlet jetty and breakwaters on the north end of Assateague Island National Seashore in 2011. Photograph by NPS.

as the shoreline retreats to extend the lifespan of the structure. Maintenance frequency may vary depending on erosion rate of the land to which it is tied, water level including storm surges, and height and integrity of the initially-built structure. Costs of maintenance depend on the level of maintenance (e.g., minor modificat on vs. complete rebuild), material used, labor used, diffi lty of accessing the site, time frame of modificat on, and regulatory and public notice requirements, among other considerations (USACE 2008).

Examples of jetty and groin projects are summarized below with cost estimates and project details. Both NPS and non-NPS examples are included.

Figure 8.5. Steel sheet-pile groin at the former location of the Cape Hatteras Lighthouse. Photograph by NPS.

1. **Columbia River Inlet, Lewis and Clark National Historic Park: Jetty Repair (2007)**
   The south jetty at the mouth of the Columbia River in Lewis and Clark National Historic Park was repaired in 2006–2007 at a cost of $1.9 million for 5,300 ft (1,615 m). The jetty is constructed of stone (USACE 2012).
   Approximate Cost: $3,585/ft ($11,176/m)
2. **Ponce de Leon Inlet, Florida: Jetty Extension (2010)**
   The south jetty at Ponce de Leon Inlet in Florida was extended by 900 ft (274 m) for $14.8 million in 2010. The extension was constructed out of light-weight stone from a Florida quarry and was a straight jetty design (Florida Department Environmental Protection 2010).
   Approximate cost: $16,444/ft ($53,950/m)
3. **Matagorda, Texas: Jetty Replacement (2010)**
   The east jetty on the mouth of the Colorado River in Matagorda, Texas, was replaced in 2010 by the US Army Corps of Engineers. The jetty was 2,780 ft (847 m) in length and constructed of 170,000 tons of rock, at a price of $25 million (MCEDC 2011).
   Approximate cost: $8,992/ft ($29,500/m)
4. **North Carolina Terminal Groin Study (2010)**
   The North Carolina legislature directed the North Carolina Coastal Resources Commission to initiate this project for the consideration of terminal groin construction in North Carolina. A study (NCCRC 2010) was conducted on the costs, benefits, a d impacts of terminal groins. Table 8.2 summarizes the results of this study and the costs for the installation and repair of terminal groins.

Table 8.2. Construction costs by material.

Construction Material	Price Per Linear Foot	Price Per Linear Meter
Rock and Stone	$1,200–$6,500	$3,937–$21,325
Concrete and Steel Sheet Pile	$4,000–$5,000	$13,123–$16,404
Timber	$3,000–$4,000	$9,843–$13,123
Geotextile	$250–1,000	$820–$3,281

Two specific e amples from the 2010 North Carolina terminal groin study are summarized below:

a. **Fort Macon, North Carolina: Terminal Groin Construction (1961–1970)**
   The terminal groin at Fort Macon was constructed between 1961 and 1970 and is a 1,530-ft (466-m) stone structure. The crest width of the groin is around 10 ft (3 m) and the base width around 60 ft (18 m). According to the authors of the study, the groin cost $2.9 million in 2009 dollars (NCCRC 2010).
   Approximate cost (2009 dollars): $1,900/ft ($6,234/m)

b. **Oregon Inlet, North Carolina: Terminal Groin Construction (1991)**
   Oregon Inlet impacts Cape Hatteras National Seashore. The terminal groin on the south side of Oregon Inlet was built in 1991 at a cost of $13.4 million. It is a stone structure 3,125 ft (952 m) long and includes a revetment on the shoreline. An estimated (2009 dollars) cost of $26.3 million for the structure was made in this study (NCCRC 2010).
   Approximate cost (2009 dollars): $8,410/ft ($27,592/m)

Benefits

Groins can create a temporary wide beach on the updrift side of the structure. Jetties limit sediment flow i to the adjacent inlet, reducing the frequency of maintenance dredging to maintain a navigable depth. Jetties also reduce the wave energy within the inlet and can widen the beach just up-drift of the structure.

Impacts and Disadvantages

Shore-perpendicular structures, such as groins and jetties, disrupt natural beach processes and alongshore sediment transport pathways. By design, these structures are meant to capture sand transported by the longshore current; this depletes the sand supply to the beach area immediately down-drift of the structure. In response, down-drift property managers often install groins on adjacent properties to counteract the increased erosion, leading to a cascading effect of groin installation. Groins may be notched to increase their permeability, allowing some sediment to pass over the groin. This strategy is used with beach nourishment projects to limit overall sediment loss and to reduce renourishment frequency.

Jetties can also hinder inlet migration and delta processes, which are natural and important parts of the stability of coastal systems that allow sediment to build marsh platforms and add sediment to the bay side of an island. Large jetties and groins can alter physical processes significa tly, which in turn can create new and different habitat. For example, a jetty can trap large quantities of sand on the updrift side, which can create beach, sand dune, or other upland coastal habitat that replace the nearshore or intertidal environment. This might be considered a benefit or the habitat type created and an impact to the pre-existing habitats and associated resources that are lost.

Breakwaters

A breakwater (figu e 8.4) is an offshore shore-parallel structure that breaks waves, reducing the wave energy reaching the beach and fostering sediment accretion between the beach and the breakwater. It is made of rock, concrete, or oyster shell (if in a low-wave environment). It can be floati g or fi ed on the ocean floor a d can be continuous or segmented or as a series of spheres (reef balls). It can be high-crested to act as wave barriers, low-crested to allow overtopping, or submerged to lessen its physical and visual impact (Nordstrom 2014). Breakwaters are often used in marinas or other areas without high wave energy (SAGE, NOAA, and USACE 2014).

Breakwaters within protected harbors are not expected to be impacted by sea level rise over a 50-year project life span (HR Wallingford 2015), although that review only considered the lowest sea level rise scenario. If sea level rises to the point that the breakwater is submerged at high tide, the breakwater would be a navigation hazard. Breakwaters exposed to increased wave height associated with sea level rise may be weakened by wave impact; extreme significa t wave heights are expected to increase by about 55% of the increase in relative sea levels, for a total increase of 155% (HR Wallingford 2015). The increased frequency of wave overtopping will reduce the ability of the breakwater to shelter the shoreline from wave energy (Heberger et al. 2009). Additionally, rising water levels will effectively move the shoreline farther from the breakwater, increasing the ability of the waves to diff act behind the structure and reducing the breakwater's effica (Heberger et al. 2009).

Costs

Initial construction costs are up to $10,000 per linear ft ($32,808/m) and an annual maintenance cost of over $500 per linear ft ($1,640/m), assuming a 50-year project life (SAGE, NOAA, and USACE 2014).

Benefits

Breakwaters reduce the force and height of waves reaching the shoreline. Sediment accretes landward of the breakwater, and in the case of high-crested breakwaters, can even create salients that connect the beach to the structure.

Breakwaters can stabilize wetlands and provide shelter for new intertidal marsh habitat to form landward of the structure (Nordstrom 2014). The rocky habitat can provide some reef function (SAGE, NOAA, and USACE 2014). Along estuarine shorelines, bagged oyster breakwaters were found to support much higher densities of live ribbed mussels than reef ball breakwaters, but both configu ations supported increased species richness of juvenile and small fi hes compared to controls (Scyphers, Powers, and Heck 2014).

Impacts and Disadvantages

Breakwaters are expensive to install in deep water, can create a navigational hazard, and can reduce water circulation. Sediment that accumulates landward of the breakwater may reduce alongshore transport, leading to downdrift erosion; this sediment can be silty and rich in organic matter. Intertidal marsh that forms landward of the breakwater may not be appropriate in that location and may replace a natural sandy beach habitat (Nordstrom 2014). Breakwaters do not provide high water protection (SAGE, NOAA, and USACE 2014).

Beach Nourishment

Beach nourishment, also referred to as renourishment or replenishment, is the placement of sand onto beaches or within the nearshore (figu e 8.6). Sand is obtained from an outside source; it is commonly dredged from an offshore location and pumped via pipelines directly onto the beach or dumped from a hopper dredge into the nearshore, or in some cases it is trucked from an inland source and dumped onto the lower beach. Nourishment replaces sand that is lost because of coastal erosion and can temporarily widen a narrow beach. Many times this process is used to mitigate erosion caused by hard structures such as groins and seawalls. The placement of sand on the beach increases the distance between vulnerable infrastructure and wave energy, which in some cases can help mitigate and postpone damage to infrastructure and property from coastal hazards. Berms may also be built when sand is added to replace dune function; they absorb wave energy before the water reaches infrastructure behind the dunes, and they serve as a sand source to nourish the beach. Dunes may be stabilized by planting vegetation and erecting sand fencing, which is described in the following section. The NPS Reference Manual 39-2: Beach Nourishment Guidance provides guidelines and best management practices for implementing beach nourishment projects where they have been deemed necessary and consistent with NPS management policies (Dallas, Eshleman, and Beavers 2012).

Figure 8.6. Beach nourishment at Assateague Island National Seashore in 2002 added sediment and widened the beach. Photograph by NPS.

Nourished beaches are subject to the same erosional forces as natural beaches (NRC 2014), and increased renourishment frequency is expected with increased sea level rise and storm impacts.

The US Fish and Wildlife Service (USFWS) has published a set of best management practices (Rice 2009) to avoid adverse impacts to biological resources including macro-invertebrates upon which fi h and birds prey, and which can be buried by sand placement. Important considerations include the timing of any sand placement relative to reproductive seasons; the quality and match of sand grains to the existing habitat; and maintaining the appropriate beach slope.

Costs

The cost of beach nourishment, like other types of coastal protection measures, varies depending on the method, location, and distance to the source sand. However, it is widely acknowledged that this method of protection can be extremely expensive, especially given that the process must be repeated frequently (commonly every few years). The cost of nourishment, including the transport and placement of the material, is commonly between \$300 and \$1,000/ft (\$984 to \$3,281/m) or between \$5 and \$30/yd^3 (\$3.80 to \$23/m^3) of sand. Below are eight beach nourishment projects in recent years within and outside of NPS coastal park units.

1. **Assateague Island, Maryland (2002)**
   A one-time beach nourishment event widened the beach by 100 ft (30 m) in the area between 1.2 and 7.5 mi (2 and 12.5 km) south of the Ocean City Inlet (figu e 8.6). The sediment was dredged from Great Gull Bank, in offshore Maryland State waters, and placed just seaward of the mean high water line to replace about 15% of the sand captured by the Ocean City Inlet since 1934 (USACE 1998). This effort cost \$13.2 million.
   Total Volume: 1,832,000 yd^3 (1.4 million m^3)
   Approximate cost: \$7/yd^3 (\$9.42/m^3)
2. **Assateague Island, Maryland (2004–present)**
   The North End Restoration project is a 25-year effort that began in 2004 to restore sediment transport to the North End, which has been eroding since the Ocean City Inlet was stabilized in 1934. Twice each year, a dredge vessel takes sand from the inlet ebb and flood t dal deltas and deposits it approximately 1.5 to 3.1 mi (2.5 to 5 km) south of the inlet, placing a volume approximately equal to the natural pre-inlet longshore transport rate. The bypassed borrow material is deposited on the crest and just seaward of the nearshore bar. The project

moved 1,990,956 yd³ (1,522,195 m³) between 2004 and 2010. The estimated cost for dredging and placing sediment, and for monitoring and administering the project, is $2 million annually (Schupp et al. 2013).
Total Volume: 188,345 yd³/year (144,000 m³/year)
Approximate project cost: $10.62/yd³ ($13.89/m³)
Approximate cost, not including monitoring program: $6 to $7/yd³ ($7.85 to $9.15 m³)

3. **Cape May Point, New Jersey (2005–ongoing)**
   Cape May had been negatively affected by the dredging of a 3-mi (5-km) canal during World War II, as well as the installation of jetties in 1911, resulting in significa t beach erosion. In 2005, USACE began a four-year renourishment cycle. Initial nourishment in 2005 consisted of 1.5 million yd³ (1,146,832 m³) at Meadows and Cape May Point as well as nourishment of the Cape May Inlet (Fox 2007; USACE 2013). Nourishment occurring through 2014 brought the total to 3.9 million yd³ (3 million m3) placed at a cost of $40.9 million (PSDS 2016).
   Total Volume (2005-2014): 3.9 million yd³ (3 million m³)
   Approximate cost: $10.45/yd³ ($13.70/m³)

4. **Harrison County, Mississippi (2007)**
   Development along the coast of Harrison County, Mississippi, has compromised the natural shoreline. Beginning in the 1950s, a seawall and human-made beach were constructed to protect the shoreline. The latest renourishment along the 24.5 mi (39 km) of beach took place in 2007, pumping 1.1 million yd³ (841,010 m³) of sand and costing about $6 million (Melby 2007; Brown, Mitchell & Alexander, Inc. 2011; PSDS 2015).
   Total Volume: 1.1 million yd³ (841,010 m³)
   Approximate cost: $5.40/yd³ ($7.13/m³)

5. **Bald Head Island, North Carolina (2010)**
   More than 150 ft (46 m) of beach had been lost on the west and south beach areas on Bald Head Island, North Carolina, by the time nourishment began in early November 2009. The dredged Cape Fear River contributed about 1.8 million yd³ (1,376,200 m³), which was pumped onto the shoreline over a four-month period at a cost of about $17 million (McGrath 2009; PSDS 2015).
   Total Volume: 1.8 million yd³ (1,376,200 m³)
   Approximate cost: $9/yd³ ($12.35/m³)

6. **West Ship Island, Mississippi (2011)**
   Ship Island, part of the Gulf Islands National Seashore, was initially divided by Hurricane Camille in 1969 and the inlet significa tly widened during Hurricane Katrina in 2005. Therefore, a three-phase project was implemented to rejoin the East and West Ship Islands (Schupp, Beavers, and Caff ey 2015, "Case Study 14: Large-Scale Restoration of Barrier Island Systems and Cultural Resource Protection through Sediment Placement"). By 2011, more than 0.5 million yd³ (almost 432,000 m³) of sand had been pumped along 10,350 ft of the West Ship Island shoreline to complete the $6 million north shore portion of the project that will protect the historic Fort Massachusetts (NPS 2011a; Kirgan 2011; USACE 2014; PSDS 2015).
   Total Volume: 565,000 yd³ (431,942 m³)
   Approximate cost: $10.61/yd³ ($13.89/m³)

Additional renourishment and sand bypassing is planned as part of the Mississippi Coastal Improvements Program project and will affect other areas of the park. Filling in Camille Cut to rejoin East and West Ship Islands is estimated to require approximately 13.5 million yd³ (10.3 million m³) of sediment. As part of the Ship Island restoration, the southern (Gulf) shoreline of East Ship Island will also be renourished with 5.5 million yd³ (4.2 million m³) of sediment. The Ship Island restoration will be accomplished in 5 phases over a 2.5-year period beginning in early to mid-2016. Natural regional sediment transport volumes will be restored by modifying future placement locations to better place material dredged from Horn Island Pass into the active littoral drift zone. The estimated cost for sand placement in Camille Cut and nourishment of East Ship Island is dependent on borrow site combinations used and is estimated at $368 million, not including monitoring costs (USACE 2014).

7. **Perdido Key, Florida (2011)**
   A sand renourishment project took place in 2011 on the south shore of Perdido Key, Florida, part of Gulf Islands National Seashore. The area had been heavily affected by Hurricane Ivan in 2004 and was considered "critically eroded." Three million yd³ (2.3 million m³) of sand from Pensacola Pass was used to restore 2 mi (3.2 km) of shoreline located between Johnson Beach and Perdido Key State Park, costing about $14.5 million (NPS 2011b; My Escambia n.d.).
   Total Volume: 3 million yd³ (2,293,664 m³)
   Approximate cost: $4.80/yd³ ($6.32/m³)

8. **Ocean City Beach, New Jersey (2013)**
   The USACE beach nourishment project at Ocean City Beach, New Jersey, in 2013 was part of a series of beach maintenance projects for the area following Hurricane Sandy. This three month renourishment began in February 2013 when 1.8 million yd³ (almost 1.4 million m³) were placed along 2.3 mi (3.7 km) of the beach. The initial $11 million project raised its cost to about $18 million, which included supplemental funds from the

Sandy disaster fund (Bergen 2013).
Total Volume: 1.8 million yd^3 *(1,376,200* m^3*)*
*Approximate cost: $10/*$yd^3$ *($13.07/*$m^3$*)*

Benefits

Beach nourishment can provide protection from coastal hazards, such as storms, by increasing beach sand volume and beach width and reducing wave energy near at-risk infrastructure. The addition of sand to the beach profile (w dth and height) can also provide protection from moderate water level rise, up to the height of the constructed beach. Nourishment is often preferred to other types of coastal protection because many consider it a "soft" approach to beach engineering, which may attract less community resistance than hard structures such as groins, revetments, seawalls, or bulkheads. Some municipalities and states (e.g., North Carolina) restrict hard structures but allow soft stabilization. The additional beach width created by nourishment can help to promote beach tourism and recreational activities. Nourishment also creates a rapid visible change in the beach, in comparison to breakwaters or groins that trap sand over a longer period of time. Constructed dunes add sand to nourish the beach, with or without structural control, and provide a foundation for additional dune growth that may be enhanced by vegetation planting or sand fencing (Benoit et al. 2007). Newly constructed dunes provide new types of upland habitat, but it is not known if they provide the same ecosystem services, including wave energy dissipation, as naturally built dunes.

Impacts and Disadvantages

Beach nourishment can have ecological, physical, and fi cal consequences. Beaches have a natural process of migration, which can accelerate during storm events. Beach migration does not end after nourishment, and continued erosion results in the need for subsequent nourishment projects within the same area, typically every few years. This short-term approach is very costly and can shut down a beach area for several months during each nourishment project. Predictions related to the durability of a nourishment project (i.e., how long the sand will last) are commonly overestimates and cost predictions are commonly underestimates (Pilkey et al. 1998). Research has also shown that nourished beaches disappear more quickly and recover more slowly from storms than natural beaches do (Pilkey et al. 1998). The cost and scale of renourishment episodes are highly likely to increase with sea level rise and with any increase in storm frequency or intensity.

Compatible sand sources for nourishment projects can be limited. Where possible, sand is often dredged from local sites for the purpose of introducing similar and compatible sediment into the beach areas of nourishment, but appropriate sources are not always available nearby. Sediment taken from nearby areas may have different proportions or ranges of grain sizes that are incompatible with existing habitat, impacting shorebird foraging, sea turtle nesting, shallow marine life, and the aesthetic quality of the beach (e.g., mudballs on previously sandy beaches). Dredging from local offshore sources may provide sediment with similar characteristics, but the dredging can disrupt the sediment transport pathway and reduce the ongoing natural sand supply to that location or other portions of the coast. Also, sediment borrow areas may become depleted as nourishment increases, thus requiring sediment to be borrowed from a greater distance or potentially from a less compatible source.

There are ecological impacts in the areas where sand is dredged and placed. Borrow pits can fill w th fi e-grained sediment that is resuspended during storm events; this in turn can impact adjacent resources (e.g., coral reefs). Borrow pits with fi e-grained sediment also typically host a different ecological community from that which would occur naturally. Sand placement may cause burial of intertidal invertebrate communities (ASMFC 2002) and sedimentation of hardbottom reef structure (Lindeman and Snyder 2002) either by direct placement on reefs or as sediment is transported by nearshore waves and currents. Nourished beaches tend to have pronounced vertical scarps, especially soon after they are placed. This scarp can impact use by animals (e.g., shorebirds, turtles), and people (e.g., safety of oversand vehicles).

Physical processes can also be impacted by beach nourishment and associated dredging. For example, dredging inlet or delta sands, or placing sediment updrift of an inlet, can alter natural inlet and delta dynamics including inlet bypassing processes and flood t dal delta sedimentation. These dynamics and processes are vital for maintaining barrier island systems; the natural maintenance that is provided by these systems promotes resilience to storms and sea level rise. Any interruption or alteration of inlet or delta processes can hinder these benefits. For e ample, tidal delta deposits are often a major source of sand for nearby beaches; taking sand from these deposits may increase shoreline retreat downdrift.

Nourishment also can encourage increased development in high-risk areas. A nourishment project can give future land owners, land developers, and real estate personnel the erroneous impression that since the beach is wider, it is stable and low risk for damage and erosion. However, beach nourishment only postpones the danger by shifting the current shoreline seaward and does not reduce or eliminate erosion. For more information on park boundaries and jurisdiction that might be impacted by beach nourishment, see NPS 39-1 Ocean and Coastal Jurisdiction Reference Manual.

Sand Fencing

A sand fence can be constructed on a beach or dune to build a new foredune or to fill gaps in une ridges by reducing wind speed or trapping sand. Fences can be made of wooden slats, plastic, or fabric attached to fence posts. Fences that run parallel to the shore can build a protective dune ridge. Two parallel lines of fencing create a wide foredune with a round crest and allow for planting dune grasses. Zig-zag configu ations can create wider dunes with lower slopes that appear more natural. Fence configu ations that maximize height of the dune are best for infrastructure protection; configu ations that create multiple crests on lower and wider dunes are best for enhancing ecological value (Nordstrom 2014). Fences have been used at many national seashores, including Assateague Island National Seashore (Schupp and Coburn 2014) and Cape Hatteras National Seashore (Schupp 2015).

Costs

Sand fences are relatively inexpensive, are easy to install, and do not often require permits.

Benefits

Sand fences can support increased vegetation growth and species richness by reducing wind stress and salt spray (Nordstrom 2014). Sand fencing can provide co-benefits by directing visitor pathways away from delicate dune and beach habitats.

Impacts

Sand fences are usually placed at a highly dynamic boundary between the beach and dune, which is important habitat for sea turtles and nesting shorebirds (Nordstrom 2014). Effective sand fences are buried as the sand is trapped, so they are not removed. When exposed by erosion events, the relict fencing material may create unwanted debris and safety hazards on the beach.

Natural and Nature-based Features (NNBF)

Shorelines can be protected by natural features, nature-based built features, other built features, and hybrids of these feature types. Nature-based features may mimic characteristics of natural features but are human constructions to provide specific se vices such as coastal risk reduction. The combination of both natural and nature-based features is referred to collectively as NNBF. The relationships and interactions among the natural and built features in the coastal system influe ce coastal vulnerability, reliability, risk, and resilience (Bridges et al. 2015).

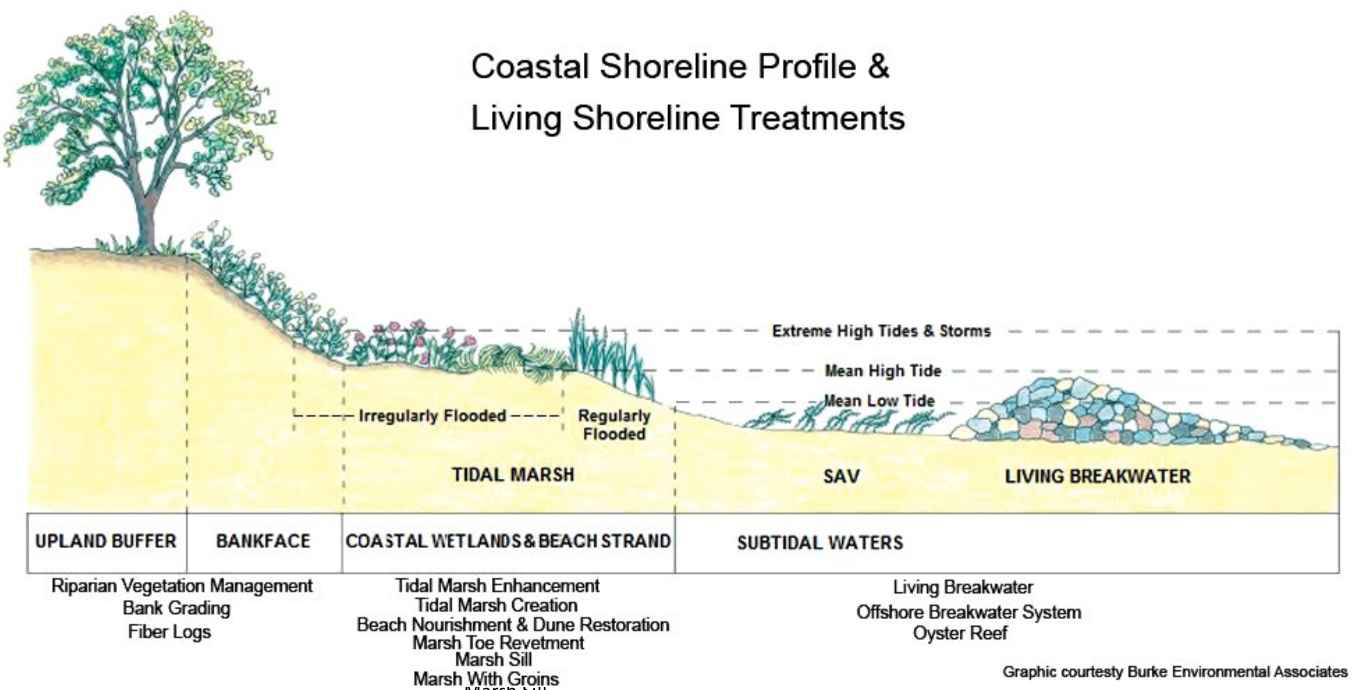
Living shorelines use natural elements, such as vegetation, to stabilize sheltered coastlines such as along estuaries. They maintain continuity of the natural land–water interface and reduce erosion while providing habitat value (NOAA 2015). For example, along low-energy estuarine shorelines, native plants can be planted so that their roots hold soil in place to reduce erosion. The plants provide a wave buffer to upland areas.

Nature-based features, also known as hybrid techniques (figu e 8.7), incorporate both nonstructural components and structural approaches (e.g., rock sill, breakwater). They have sometimes been referred to as "living shorelines," a misnomer because the living component can be used as a façade to build what is functionally a hardened shoreline. An example is the combination of plantings with edging (e.g., geotextile tubes, oyster reef) or rock sills to hold the toe of the existing slope in place (see Schupp, Beavers, and Caff ey 2015, "Case Study 3: Shell Mound Sites Threatened by Sea Level Rise and Erosion"). Sills are low edges that protect marsh grass fringe by breaking approaching waves. Breaks in the sills allow fauna to cross through the barrier. Building a sill system requires encroachment beyond the shoreline. Sand may be added with marsh grass plantings to provide stability and will be necessary at sites with a wind fetch that exceeds 0.5 mi (0.8 km). Creating this system changes existing habitat; the eroding bank, narrow beach and nearshore are converted to a stable bank, marsh and stone sill (Benoit et al. 2007).

It is important to have ongoing maintenance of the living shoreline, including replanting vegetation as needed, trimming tree branches, removing debris, and removing any interfering invasive species (NOAA 2015). The natural feature, if not maintained correctly, may damage the hard structure; an example would be when trees colonize the shoreline and then fall in a storm, causing their roots to unseat the hard structure. Conversely, the structural components can interrupt natural processes or the non-structural components can fail.

Figure 8.7. Examples of hybrid approaches to living shorelines. ***Notes: (a) This hybrid approach to a living shoreline uses natural and nature-based features by combining a planted marsh with a rock sill. Photograph from Bilcovic and Mitchell (2011). (b) The vegetation component of this hybrid approach at GATE was unsuccessful, leaving only shoreline armoring. Photograph by NPS.***

NOAA Fisheries Office Habitat Conservation provides guidance for living shoreline planning and implementation, including a diagram (figu e 8.8) showing a continuum of treatment options (NOAA 2016); other good sources are Benoit et al. (2007) and the Maryland Chesapeake Bay experience over the past decades (Maryland Department of Environment 2008). In general, nonstructural approaches are better suited to low wave energy environs, while hybrid techniques are typically applied in areas of medium to high wave energy (Bilcovic and Mitchell 2011). The non-structural component should be appropriately designed for the environment.



Marsh Sill
Marsh With Groins

Graphic courtesy Burke Environmental Associates

Figure 8.8. Living shoreline options for stabilizing estuarine shorelines. Figure by Burke Environmental Associates available via National Geographic, http://nationalgeographic.org/encyclopedia/living-shoreline/ (accessed 9 September 2016).

A hybrid engineering approach known as Systems Approach to Geomorphic Engineering (SAGE) is being advocated by a Community of Practice of numerous of agencies and organizations, including state and federal government (USACE and NOAA), academic institutions, NGOs, and private sector. The goals are to stabilize the shoreline, reduce current rates of shoreline erosion and storm damage, provide ecosystem services (such as habitat for fi h and other aquatic species), increase flood torage capacity, and maintain connections between land and water ecosystems to enhance ecosystem resilience (SAGE, NOAA, and USACE 2014). SAGE considers the landscape view of how multiple site management strategies work (or do not work) together, such as a protected area with no shoreline structures next to a levee or living shoreline or seawall. SAGE leverages partnerships across entities and jursidictions making these decisions, and provides expertise and information needed to make them.

Recent research suggests that the biggest cause of salt marsh erosion is waves driven by moderate storms, not occasional major events such as hurricanes and other strong storms, which contribute less than one percent of deterioration (Leonardi, Ganju, and Fagherazzi 2016). Storm impacts on wetlands often include erosion, stripped vegetation, and salinity burn, all of which can decrease long-term productivity; storms may also introduce new sediment that increases long-term sustainability of wetlands with respect to sea level rise (Bridges et al. 2015). Long-term consequences for wetland systems depends on many factors, including the size of the wetland, proximity of the wetland to a storm track, and post-storm conditions (for example, high post-storm precipitation will reduce the effects of salinity burn) (Bridges et al. 2015). Salt marsh elevation may not be able to keep pace with the rate of sea level rise (Bridges et al. 2015). Many components of natural infrastructure, including vegetation and oyster reefs, may be increasingly vulnerable to climate-related changes, such as warmer water, disease, invasive species, and changes in salinity, water temperature, and air temperature (Melillo, Richmond, and Yohe 2014). Planning for hybrid projects must consider the lifespan of the living component and the possibility that the living component will fail and the hard structure will remain.

The draft proposed 2017 Nationwide Permits issued by the USACE includes a new Nationwide Permit (NWP B) for the construction and maintenance of living shorelines, which would be separate from NWP 13, which authorizes bank stabilization activities (USACE 2016). Doing a project under a NWP decreases the processing times and permit application costs associated with obtaining authorization under Section 404 of the Clean Water Act and Section 10 of the Rivers and Harbors Act of 1899.

Costs

Estuarine vegetation planting has an initial construction cost of up to $1,000 per linear ft ($3,280/m) and an annual maintenance cost of up to $100 per linear ft ($328/m), assuming a 50-year project life. Construction of edging or sill in combination with vegetation planting has an initial construction cost of up to $2,000 per linear ft ($6,562/m) and an annual maintenance cost of up to $100 per linear ft ($328/m), assuming a 50-year project life (SAGE, NOAA, and USACE 2014).

Costs will vary depending on the materials used. Installation may require professionals. Long-term maintenance is required, such as post-storm replanting.

Benefits

Living shorelines are increasingly promoted as a way to protect estuarine shorelines, as an alternative to armoring, which can result in habitat fragmentation or loss, reduced capacity to fi ter pollutants, reduced biotic integrity, increases in invasive species, and disturbance of sediment budgets sustaining adjacent properties (Bilcovic and Mitchell 2011). Vegetation alone or planted in combination with the edging or sill structures will dissipate wave energy, provide habitat and ecosystem services, and slow inland water transfer. Planting submerged aquatic vegetation such as seagrass stabilizes sediment and may contribute to wave attenuation at low tide (Koch 2001). Seagrass beds are most effective at attenuating waves (and thus protecting the shoreline) when seagrass height reaches the water surface (Fonseca and Cahalan 1992).

Impacts and Disadvantages

Estuarine vegetation planting may increase or decrease storm surge water levels (and therefore wave energy) depending on the storm and the water level relative to the planted elevation. They may be misperceived as protecting uplands from high water, which they are not intended to do. Vegetation survival may be limited or unsuccessful (figu e 8.7b) and may depend on competition with invasive species (SAGE, NOAA, and USACE 2014).

The value of seagrass beds for shore protection is limited by their seasonality. During the winter months, seagrasses in temperate areas become less dense or may even disappear.

Hybrid techniques can be more effective at reducing erosion, but the structural component will disrupt sediment processes and many of the benefits as a ternatives to traditional armoring are lost. When a hybrid approach is planned, there needs to be a contingency plan for removing the structures or restoring the vegetation if the initial vegetation does not survive. Permitting processes may be complicated because the existing regulatory process is centered on traditional hard stabilization techniques.

Redesign the Structure

Adapting the design of a structure is another way to protect a structure, or the function of a structure, in place (figu e 8.9). Design options for existing infrastructure include elevating the structure, elevating systems within the structure, or waterproofi g mechanical systems (as described in "Chapter 9 Lessons Learned from Hurricane Sandy"). New construction design may include elements such as sacrific al construction that is expected to be destroyed during an event, but will minimize clean up or hazards. Historic infrastructure may now be insuffi ent for modern conditions, such as stream culverts in places experiencing increased high flow e ents. Enlarging or re-engineering culverts (see Schupp, Beavers, and Caff ey 2015, "Case Study 15: Rehabilitating Stream Crossings on Historic Roads") can prevent erosion and road damage and may provide additional benefits (e.g., improving fi h passage).

Costs

Costs may be lower than complete removal or relocation of the structure. Adaptive maintenance costs and requirements may be higher than for typical infrastructure; for example, adapting the electrical panels to withstand future inundation at Ellis Island required innovation and upgrades to standard electrical panels (see "Chapter 9 Lessons Learned from Hurricane Sandy").

Benefits

Elevating a structure can prolong its accessibility and functionality for many years and may allow use of the structure until the end of its expected serviceable years. This option postpones or eliminates the need to fi d and impact a new site. It also allows historical structures to remain within an associated historic or cultural landscape.

Impacts and Disadvantages

Pilings used to elevate a structure may be undermined by continued shoreline erosion and changes in groundwater elevation. Means of accessing the structure may change, for example, if roads are undermined by continued erosion. Utility systems for elevated structures can be problematic, especially if buried, as they are vulnerable where they come up to the structure. This approach is likely not feasible as a permanent solution, and additional measures such as relocation or removal may need to be considered as shoreline vulnerability increases.

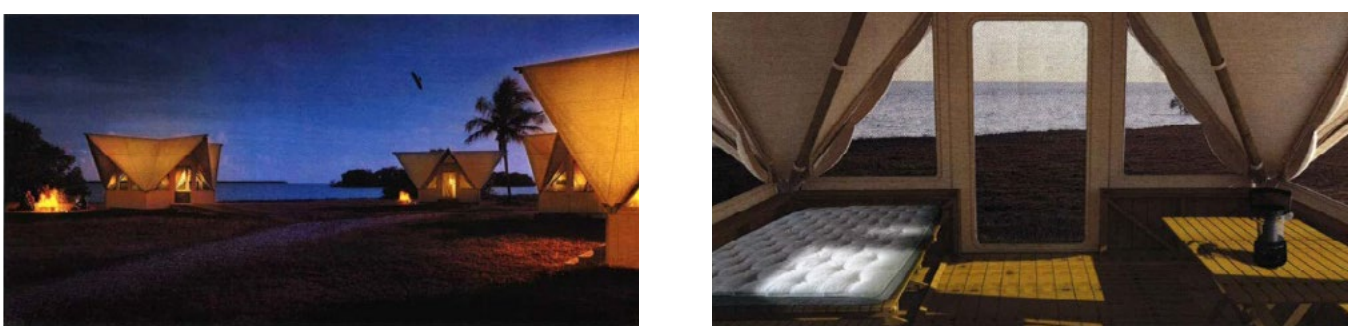


Figure 8.9. Visitor facilities have been redesigned at Everglades National Park; the new eco-tents are designed to be portable and can be moved in advance of storms. Images by NPS.

Figure 8.10. In this example of relocation and retreat, the Cape Hatteras lighthouse was moved inland using a railway. Photograph by NPS.

Relocate

Structure relocation is the strategy of transporting a structure from a vulnerable area and placing it in a more stable location (figu e 8.10). This can reduce structure vulnerability to threats, such as undermining caused by shoreline erosion, damage from wave impact, boring by marine organisms, and sea level rise. A structure can be moved as a whole or in parts using a flat-bed tr ck or temporary rails. The transport distance can vary, but most examples of relocation have been less than 500 feet inland from the original location. Infrastructure can also be replaced by structures that are designed to be moved landward to a new site, usually once or twice away from an eroding shoreline, or by portable structures that are moved off site seasonally or ahead of a storm and then returned (see Schupp, Beavers, and Caff ey 2015, "Case Study 16 Relocating Visitor Facilities Threatened by Accelerated Erosion"). Relocation should also consider the vulnerability of the new site to climate change.

Costs

The cost of structure relocation ranges from $800 to $40,000 per linear ft ($2,625 to $131,234/m) of movement depending on the size of the structure and method of relocation. Various projects within this range are described below.

1. **Hunting Island, South Carolina: Lighthouse Relocation (1889)**
   The second Hunting Island Lighthouse, fir t lit on July 1, 1875, was an iron building capable of being relocated. It was thought to be protected by a jetty constructed in 1886, until one year later a storm resulted in the shoreline being only 152 ft (46 m) from the lighthouse. In 1889, the relocation of Hunting Island Lighthouse, 6,600 ft (2,012 m) inland from the original site, lasted six months and cost $51,000 ($1.3 million in 2013 dollars) (Lighthouse Friends 2001b).
   Approximate cost of relocation (2013 dollars): $197/ft ($646/m)
2. **Block Island Southeast, Rhode Island: Lighthouse Relocation (1993)**
   Block Island Southeast Lighthouse, built in 1874, stood only 75 ft (23 m) from the edge of a bluff formed by substantial erosion. It was moved 300 ft (91 m) farther inland in August 1993 over a period of 19 days at a cost of approximately $2 million (Lighthouse Friends 2001c).
   Approximate cost of relocation: $6,666/ft ($21,870/m)
3. **Highland, Cape Cod, Massachusetts: Lighthouse Relocation (1996)**
   The relocation of Cape Cod's Highland Lighthouse, which is within Cape Cod National Seashore, occurred over a two-week period in July 1996. The Coast Guard Light was transported 450 ft (137 m) westward to escape the ongoing erosion occurring on the Highlands of Truro. The cost of this relocation was about $1.54 million (Lighthouse Friends 2001a; NPS 2014a).
   Approximate cost of relocation: $3,422/ft ($11,227/m)
4. **Cape Cod, Massachusetts: Lighthouse Relocation (1996)**
   Nauset Lighthouse was only 36 ft (11 m) from a cliff in Eastham, Massachusetts, when it was relocated in 1996. The privately owned lighthouse, which is within Cape Cod National Seashore, was built to be moved, and had already been moved to Eastham from Chatham in the 1870s. Nauset Lighthouse was relocated 300 ft (91 m) inland in three days at a cost of $253,000 (Nauset Light Preservation Society 1996; NPS 2014a).
   Approximate cost of relocation: $843/ft ($2766/m)
5. **Herring Cove Beach, Cape Cod, Massachusetts: Structure Relocation (2013–ongoing)**
   A retreat and mitigation plan began in 2013 to relocate structures on Herring Cove Beach, part of Cape Cod National Seashore in Provincetown, Massachusetts, (see Schupp, Beavers, and Caff ey 2015, "Case Study: 17 Reducing Vulnerability of Coastal Visitor Facilities"). This included relocation of the north parking lot, a bath house and concession stand, and removal of a revetment constructed in the 1950s. The plan intended a one-time retreat to protect the structures for 50 years. The relocation included moving the north parking lot 125 ft (38 m) inland to an elevation of 15 ft (4.6 m) above sea level. The bathhouse and concession stand were replaced with a moveable, elevated structure

approximately 100 ft (30 m) landward of the former location. The cost of the retreat strategy was estimated at $4.5 million with an $825,000, 25-year maintenance plan (NPS 2013).
Approximate cost of relocation: $36,000/ft ($118,421/m)

Benefits

Structure relocation or "managed retreat" can be a long-term solution for infrastructure as sea level rise, erosion, and storms affect coastal national parks now and in the future. Relocation can have long-term fi cal benefits because removing the structure from the hazardous area can significa tly reduce the need for repair and maintenance, and by reducing interest in expensive hard stabilization structures (e.g., seawalls, groins, and bulkheads) and beach nourishment, which offer only temporary protection. Natural resources may also benefit from a managed retreat strategy because the shoreline can be allowed to migrate and function naturally.

Impacts and Disadvantages

The repeated cost and maintenance requirements of moving portable structures ahead of storms can be significa t although likely lower than replacing the structures or mitigating damages and cleanup from structures that the storm moves into sensitive areas (e.g., removing damaged structures from the marsh). It may be diffi lt to locate an appropriate site for relocation due to construction impacts on resources at a new undeveloped site or a lack of open sites within highly developed urban areas. In the case of historical structures, relocation will cause the loss of historical context. Resistance within local communities and from other stakeholders can also arise. Some infrastructure may be particularly diffi lt to move, such as large complex structures including power plants, water treatment facilities, and major roads.

Abandon in Place

The National Park Service will not always be able to maintain infrastructure in place. Certain types of nonessential infrastructure become obsolete over time, particularly within the National Park Service. Many units have structures, buildings, and roads that are never used by the public, that no longer provide their original intended service, or that have a historic value that is not essential to the interpretive themes of the park (Nordstrom and Jackson 2016). Other structures may be significa t but become prohibitively expensive to maintain and repair, and the park may lack staff and funding to carry out this maintenance. In these cases, parks may want to consider the adaptation option of letting the structure deteriorate and abandoning it in place. For cultural resources, the related strategy of Document and Release (table 5.4 in "Chapter 5 Cultural Resources") requires documentation of the resource, its condition, and the decision.

Costs

Abandoning in place reduces maintenance needs but creates new costs including preparing a structure for abandonment, including the NEPA and the NHPA compliance processes; securing the structure, removal of potentially hazardous materials; and documentation or data recovery where appropriate. This action may create an attractive nuisance where people are attracted to explore a structure that is unsafe. Continued deterioration may necessitate the eventual demolition and removal of the structure.

Benefits

Abandoning in place can have long-term fi cal benefits y reducing the need for ongoing repair and maintenance of the structure. This strategy may also eliminate the need for protective engineering structures and associated impacts to adjacent resources. Allowing no longer effective shoreline protection structures to deteriorate in place may allow the re-establishment of coastal landforms when the structure has deteriorated to a degree that is no longer interfering with natural processes (Nordstrom and Jackson 2016). The abandoned structure provides interpretive opportunities related to climate change including sea level rise impacts and the different conditions when the structure was built.

Impacts and Disadvantages

Impacts of abandoning in place include the deterioration and, over time, the demolition of infrastructure that may have historical or other functional value to the public. There also may be negative impacts on the local environment, such as introduction of hazardous materials or unsecured items that may be displaced during a storm if regular inspections to the infrastructure are not completed or if there is not funding for removal of the structures before they become hazardous. "Chapter 9 Lessons Learned from Hurricane Sandy" for a discussion of infrastructure that has deteriorated and been abandoned in place, especially the groins at Fort Tilden and numerous buildings at GATE.

Take Home Messages

- Shoreline stabilization mechanisms can protect resources in place but are not long-term solutions and have trade-offs, including disruption of natural processes.
- Beach nourishment can be a costly short-term effort. There are ecological and physical consequences of dredging sand from other locations and placement of sediment on intertidal and nearshore habitats.
- The effectiveness of natural and nature-based features for shoreline protection is site-specific. Their suitability as a long-term alternative depends on ability to adapt to climate change, design, and compatibility with local conditions.
- Consider opportunities to redesign and relocate facilities, and to replace facilities with portable structures. Evaluate the maintenance costs and non-standard costs associated with these alternatives.

References

Atlantic States Marine Fisheries Commission (ASMFC). 2002. Beach Nourishment: A Review of the Biological and Physical Impacts. ASMFC Habitat Management Series # 7. Atlantic States Marine Fisheries Commission, Washington, DC. http://www.asmfc.org/uploads/file/beach ourishment.pdf (accessed 12 May 2016).

Associated Press. 2013. $40M steel sea wall to protect Sandy-ravaged towns to Mantoloking, Brick. 20 August 2013. NJ.com. http://www.nj.com/news/index.ssf/2013/08/40m_steel_sea_wall_to_protect_sandy-ravaged_towns_of_mantoloking_brick.html (accessed March 2014).

Benoit, J., C. S. Hardaway, D. Hernandez, R. Holman, E. Koch, N. McLellan, S. Peterson, D. Reed, and D. Suman. 2007. Mitigating shore erosion along sheltered coasts. National Research Council of the National Academies, Washington, DC. http://www.nap.edu/catalog/11764/mitigating-shore-erosion-along-sheltered-coasts (accessed 8 April 2016).

Bergen, D. 2013. Ocean City Beach Project is Complete. 31 May 2013. OceanCityPatch. http://oceancity.patch.com/groups/summer/p/ocean-city-beach-project-is-complete (accessed March 2014).

Bilcovic, D. M., and M. Mitchell. 2011. Ecological and Erosion Protection Functions of Chesapeake Bay Living Shorelines. Final Report to Chesapeake Bay Trust, National Oceanic and Atmospheric Administration (NOAA) Restoration Center, and the Maryland Department of the Environment, December 2011. Virginia Institute of Marine Science at the College of William and Mary, Gloucester Point, VA.

Bridges, T. S., K. A. Burks-Copes, M. E. Bates, Z. Collier, C. J. Fischenich, C. D. Piercy, E. J. Russo, D. J. Shafer, B. C. Suedel, J. Z. Gailani, J. D. Rosati, T. V. Wamsley, P. W. Wagner, L. D. Leuck, and E. A. Vuxton. 2015. Use of Natural and Nature-Based Features (NNBF) for Coastal Resilience. Final Report for the U.S. Army Corps of Engineers ERDC SR-15-1. US Army Engineer Research and Development Center, Vicksburg, MS. http://www.nad.usace.army.mil/Portals/40/docs/NACCS/NNBF%20FINAL.pdf (accessed 11 February 2015).

Brown, Mitchell & Alexander, Inc. 2011. Harrison County Sand Beach Renourishment. Report. BMA, Gulfport, MS.

Chapman, M. G., and A. J. Underwood. 2011. Evaluation of ecological engineering of “armored” shorelines to improve their value as habitat. Journal of Experimental Marine Biology and Ecology 400: 302-313.

Coburn, A.S., A.D. Griffith, and R.S. Young. 2010. Inventory of coastal engineering projects in coastal national parks. Natural Resource Technical Report NPS/NRPC/GRD/NRTR—2010/373. National Park Service, Fort Collins, CO. https://irma.nps.gov/DataStore/DownloadFile/418829 (accessed 10 August 2016).

Conti, K. 2015. “Storms taking toll on towns’ sea walls.” Boston Globe, 25 December 2015. https://www.bostonglobe.com/metro/regionals/south/2015/12/25/coastal-towns-hope-seawalls-can-withstand-winter-inevitable-storms/OKb799ePXbFmAR3uCzEuQL/story.html (accessed 11 May 2016).

Dallas, K. L., J. Eshleman, and R. Beavers. 2012. National Park Service beach nourishment guidance. RM 39-2. Natural Resource Technical Report NPS/NRSS/GRD/NRTR—2012/581. National Park Service, Fort Collins, CO. https://irma.nps.gov/App/Reference/Profile/218511 (accessed 10 August 2016).

Florida Department of Environmental Protection. 2010. Permit Modificat on for Ponce De Leon Inlet South Jetty Extension.

Fonseca, M. S., and J. A. Cahalan. 1992. A preliminary evaluation of wave attenuation for four species of seagrass. Estuarine, Coastal and Shelf Science 35:565-576.

Fox, K. 2007. Beach Replenishment – A Blessing or a Curse. Cape May Magazine. Cape May, NJ. http://www.capemay.com/Editorial/january09/beach-replenishment.html (accessed March 2014).

Glasby, T. M., S. D. Connell, M. G. Holloway, and C. L. Hewitt. 2007. Nonindigenous biota on artific al structures: could creation facilitate biological invasions? Marine Biology 151:887–895. http://link.springer.com/article/10.1007%2Fs00227-006-0552-5 (accessed 18 March 2016).

Heberger, M., H. Cooley, P. Herrrrera, P. H. Gleick, and E. Moore. 2009. The impacts of sea-level rise on the California Coast. California Energy Commission Final Report CEC-500-2009-024-F. California Climate Change Center. http://www.energy.ca.gov/2009publications/CEC-500-2009-024/CEC-500-2009-024-F.PDF (accessed 18 February 2015).

HR Wallingford. 2015. North Atlantic coast of the USA - sea level change vulnerability and adaptation measures. Final report to the U.S. Army Corps of Engineers. MCR5188-RT002-R02-00. HR Wallingford, Oxfordshire, UK. http://www.nad.usace.army.mil/Portals/40/docs/ComprehensiveStudy/SeaLevelChange_Vulnerability_AdaptationMeasures_March2015.pdf (accessed 12 February 2015).

Kirgan, H. 2011. East, West Ship islands to be rejoined in $300 million project. 23 September 2011. The Mississippi Press. http://blog.gulfl ve.com/mississippi-press-news/2011/09/east_west_ship_islands_to_be_r.html (accessed March 2014).

Koch, E. W. 2001. Beyond light: Physical, geological and geochemical parameters as possible submersed aquatic vegetation habitat requirements. Estuaries 24:1-17.

Leidersdorf, C. B., P. E. Gadd, and W. G. McDougal. 1989. Articulated concrete mat slope protection. Pages 2400-2415 in B. L. Edge, editor. Proceedings of Coastal Engineering 1988. http://ascelibrary.org/doi/abs/10.1061/9780872626874.178 (accessed 16 March 2016).

Lindeman, K. C., and D. B. Snyder. 1999. Nearshore hardbottom fi hes of southeast Florida and effects of habitat burial caused by dredging. Fishery Bulletin 97: 508-525. http://my.fit.e u/~lindeman/1999%20Nearshore%20reefs%20and%20dredging.pdf (accessed 12 May 2016).

Leonardi, N., N. K. Ganju, and S. Fagherazzi. 2016. A linear relationship between wave power and erosion determines salt-marsh resilience to violent storms and hurricanes. Proceedings of the National Academy of Sciences 113(1): 64-68.

Lighthouse Friends. 2001a. Cape Cod (Highland) MA. Web page. http://www.lighthousefriends.com/light.asp?ID=491(accessed March 2014).

Lighthouse Friends. 2001b. Hunting Island, SC. Web page. http://www.lighthousefriends.com/light.asp?ID=332 (accessed March 2014).

Lighthouse Friends. 2001c. Block Island Southeast, RI. Web page. http://www.lighthousefriends.com/light.asp?ID=41(accessed March 2014).

Martin, D., F. Bertasi, M. A. Colangelo, M. de Vries, M. Frost, S. J. Hawkins, E. Macpherson, P. S. Moschella, M. P. Satta, R. C. Thompson, and V. U. Ceccherelli. 2005. Ecological impact of coastal defense structures on sediment and mobile fauna: evaluating and forecasting consequences of unavoidable modificat ons of native habitats. Coastal Engineering 52:1027-1051.

Maryland Department of Environment. 2008. Shore Erosion Control Guidelines for Waterfront Property Owners. 2nd edition. Maryland Department of Environment Water Management Administration, Annapolis, MD. http://dnr2.maryland.gov/ccs/Publication/Shoreerostext.pdf (accessed August 2016).

Matagorda County Economic Development Corporation (MCEDC). 2011. The Port of Bay City Authority New East Jetty. Beaches, Bays, Birds, and Business 5(1). Matagorda County Economic Development Corporation, Bay City, TX. http://classic.edsuite.com/proposals/proposals_259/mcedc_newsletter_january_2011_fi_13.pd (accessed March 2014).

McGrath, G. 2009. Bald Head Island beach renourishment project is accelerated – slightly. 22 September 2009. StarNews. http://www.starnewsonline.com/article/20090922/articles/909229932 (accessed March 2014).

Melby, P. 2007. Experimental Beach Landscape 12 Year Study Results: The Evolution of a Model Landscape Design and Management Plan for the Manmade Beach in Harrison County, Mississippi. Unpublished report. http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.553.8469&rep=rep1&type=pdf (accessed March 2014).

Melillo, J. M., T. C. Richmond, and G. W. Yohe [eds.]. 2014. Climate Change Impacts in the United States: The Third National Climate Assessment. U.S. Global Change Research Program, 841 pp. doi:10.7930/J0Z31WJ2.

My Escambia. No date. Perdido Key Beach Nourishment. Web page. (accessed March 2014; no longer available).

Moschella, P. S., M. Abbiati, P. Aberg, L. Airoldi, J. M. Anderson, F. Bacchiocchi, F. Bulleri, G. E. Dinesen, M. Frost, E. Gacia, L. Granhag, P. R. Jonsson, M. P. Satta, A. Sundelöf, R. C. Thompson, and S. J. Hawkins. 2005. Low-crested coastal defence structures as artific al habitats for marine life: using ecological criteria in design. Coastal Engineering 52: 1053-1071. http://www.sciencedirect.com/science/article/pii/S0378383905001146 (accessed 10 August 2016).

National Research Council (NRC). 2014. Reducing coastal risk on the East and Gulf Coasts. National Academies Press, Washington, DC. http://www.nap.edu/catalog/18811/reducing-coastal-risk-on-the-east-and-gulf-coasts (accessed 10 August 2016).

Nauset Light Preservation Society. 1996. Moving Nauset Light 1996. Web page. Eastham, MA. http://www.nausetlight.org/NLmove.htm (accessed March 2014).

National Oceanic and Atmospheric Administration (NOAA). 2015. Guidance for Considering the Use of Living Shorelines. NOAA Living Shorelines Program, Silver Spring, MD. http://www.habitat.noaa.gov/pdf/noaa_guidance_for_considering_the_use_of_living_shorelines_2015.pdf (accessed 17 March 2016).

NOAA. 2016. Living Shoreline Planning and Implementation. Web page. http://www.habitat.noaa.gov/restoration/techniques/lsimplementation.html (accessed 18 March 2016).

National Park Service (NPS). 2011a. Beach Renourishment on West Ship Island. 22 November 2011. Press Release. Gulf Islands National Seashore, Gulf Breeze, FL.

NPS. 2011b. Perdido Key Renourishment Project. 14 November 2011. Press Release. Gulf Islands National Seashore, Gulf Breeze, FL.

NPS. 2012. Design and repair method for the failing bulkheads and completing the repairs/replacement of the bulkhead. GATE 145326. FedBizOpps Solicitation Number P12PS03193. https://www.fbo.gov/?s=opportunity&mode=form&id=bf4d33-4f28dba5444733715f4082ae26&tab=core&_cview=0 (accessed March 2014).

NPS. 2013. Cape Cod National Seashore Herring Cove Beach North Public Access Site Plan Environmental Assessment. Report. National Park Service, Washington, DC. http://parkplanning.nps.gov/document.cfm?parkID=217&projectID=44437&document-ID=55670 (accessed March 2014).

NPS. 2014a. “Lighthouse Moves.” Web page. Cape Cod National Seashore, Wellfleet, MA. http://www.nps.gov/caco/historyculture/lighthouse-moves.htm (accessed March 2014).

NPS. 2014b. “Thomas Jefferson Memorial Seawall.” Web page. National Mall & Memorial Parks, Washington, DC. http://www.nps.gov/nama/planyourvisit/thomas-jefferson-memorial-seawall.htm (accessed March 2014).

Nordstrom, K. F. 2014. Living with shore protection structures: A review. Estuarine, Coastal and Shelf Science 150: 11-23. http://dx.doi.org/10.1016/j.ecss.2013.11.003 (accessed 16 March 2016).

Nordstrom, K. F., and N. L. Jackson. 2016. Facilitating migration of coastal landforms and habitats by removing shore protection structures: An adaptation strategy for Northeast Region units of the National Park Service. Natural Resource Report NPS/NER/NRR—2016/1240. National Park Service, Fort Collins, CO. https://irma.nps.gov/DataStore/Reference/Profile/223027 (accessed 9 August 2016).

North Carolina Coastal Resources Commission (NCCRC). 2010. North Carolina Terminal Groin Study Final Report. Moffatt and Nichol, Raleigh, NC. http://portal.ncdenr.org/web/cm/fi al-terminal-groin-study-report (accessed January 2015).

Pilkey, O. H., W. J. Neal, S. R. Riggs, C. A. Webb, D. M. Bush, D. F. Pilkey, J. Bullock, and B. A. Cowan. 1998. The North Carolina Shore and Its Barrier Islands: Restless Ribbons of Sand. Duke University Press, Durham, NC.

Pister, B. 2009. Urban marine ecology in southern California: the ability of riprap structures to serve as rocky intertidal habitat. Marine Biology 156(5): 861-873. doi: 10.1007/s00227-009-1130-4 (accessed 18 March 2016).

Program for the Study of Developed Shorelines (PSDS). 2015. Beach Nourishment Viewer. Online Database. Western Carolina University, Cullowhee, NC. http://beachnourishment.wcu.edu/ (accessed 9 January 2015).

PSDS. 2016. Beach Nourishment Viewer. Online Database. Western Carolina University, Cullowhee, NC. http://psds.wcu.edu/projects-research/beach-nourishment/ (accessed 11 May 2016).

Rice, T. M. 2009. Best management practices for shoreline stabilization to avoid and minimize adverse environmental impacts. Prepared for the USFWS, Panama City Ecological Services Field Office, anama City, FL. http://www.fws.gov/charleston/pdf/PIPL/BMPs%20For%20Shoreline%20Stabilization%20To%20Avoid%20And%20Minimize%20Adverse%20Environmental%20Impacts.pdf (accessed 18 March 2016).

SAGE, NOAA, and USACE. 2014. Natural and Structural Measures for Shoreline Stabilization. Brochure. https://coast.noaa.gov/data/digitalcoast/pdf/living-shoreline.pdf (accessed 17 April 2015).

Schupp, C. A., N. T. Winn, T. L. Pearl, J. P. Kumer, T. J. B. Carruthers, and C. S. Zimmerman. 2013. Restoration of overwash processes creates piping plover (Charadrius melodus) habitat on a barrier island (Assateague Island, Maryland). Estuarine, Coastal and Shelf Science 116:11-20.

Schupp, C. A. 2015. Cape Hatteras National Seashore: Geologic Resources Inventory report. Natural Resource Report NPS/NRSS/GRD/NRR—2015/964. National Park Service, Fort Collins, CO. https://irma.nps.gov/DataStore/Reference/Profile/222201 (accessed 10 August 2016).

Schupp, C., and A. Coburn. 2015. Inventory of coastal engineering projects within Assateague Island National Seashore. Natural Resource Report NPS/NRPC/GRD/NRR—2015/914. National Park Service, Fort Collins, CO. https://irma.nps.gov/DataStore/Reference/Profile/222009 (accessed 10 August 2016).

Schupp, C. A., R. L. Beavers, and M. Caff ey [eds.]. 2015. Coastal Adaptation Strategies: Case Studies. NPS 999/129700. National Park Service, Fort Collins, CO. https://www.nps.gov/subjects/climatechange/coastaladaptationstrategies.htm (accessed 10 August 2016).

Scyphers, S. B., S. P. Powers, and K. L. Heck. 2015. Ecological Value of Submerged Breakwaters for Habitat Enhancement on a Residential Scale. Environmental Management 55(2): 383-391.

Shields, B. 2013. New Seawall Being Built To Protect Scituate Lighthouse, Coast. 3 October 2013. Televised news report. WBZ-TV, CBS Boston. http://boston.cbslocal.com/2013/10/03/new-seawall-being-built-to-protect-scituate-lighthouse-coast/ (accessed March 2014).

Spanger-Siegfried, E., M. F. Fitzpatrick, and K. Dahl. 2014. Encroaching tides: How sea level rise and tidal floodi g threaten U.S. East and Gulf Coast communities over the next 30 years. Union of Concerned Scientists, Cambridge, MA.

Thompson, L. 2012. Cost estimate for Seattle seawall sinks to $300 million. 23 April 2012. The Seattle Times. http://old.seattletimes.com/text/2018055008.html (accessed August 2016).

Titus, J. G., and E. M. Strange. 2008. "Background Documents Supporting Climate Change Science Program Synthesis and Assessment Product 4.1, Coastal Elevations and Sensitivity to Sea-Level Rise." EPA 430R07004. US EPA, Washington, DC. 354 pp. http://papers.risingsea.net/EPA-sea-level-rise-elevations-wetlands-ecosystems-2008.html (accessed 10 August 2016).

Trufant, J. 2013. Work on Marshfi ld sea wall nearly fini hed. 19 October 2013. The Patriot Ledger. http://www.patriotledger.com/news/x1275634087/Work-on-Marshfi ld-sea-wall-nearly-fini hed (accessed March 2014).

Tyrrell, M. C., and J. E. Byers. 2007. Do artific al substrates favor nonindigenous fouling species over native species? J Exp Mar Biol Ecol 342:54–60. http://www.sciencedirect.com/science/article/pii/S0022098106005739 (accessed 18 March 2016).

US Army Corps of Engineers (USACE). 1998. Appendix D: Restoration of Assateague Island. Ocean City, Maryland, and vicinity water resources study fi al integrated feasibility report and environmental impact statement. US Army Corps of Engineers Baltimore District, Baltimore, Maryland, USA.

USACE. 2005. Montauk Point, New York Hurricane and Storm Damage Reduction Study Final Feasibility Report and Environmental Impact Statement: Report Summary. US Army Corps of Engineers New York District, New York, NY. http://www.usace.army.mil/portals/2/docs/civilworks/cwrb/montauk/montauk_point_project_summary.pdf (accessed 9 January 2015).

USACE. 2007. Y-Harker's Island Shoreline Stabilization Project, National Park Service, Cape Lookout National Seashore, Carteret County, North Carolina. Notice of Contract Award for FedBizOpps Solicitation Number W912HN-06-B-0071. US Army Corps of Engineers Savannah District, Savannah, GA. https://www.fbo.gov/

USACE. 2008. Coastal Engineering Manual- Part V. Engineer Manual 1110-2-1100, US Army Corps of Engineers, Washington, D.C. (in 6 volumes). 1 August 2008 (Change 2). http://www.publications.usace.army.mil/USACEPublications/EngineerManuals.aspx?udt_43544_param_page=4 (accessed 17 December 2015).

USACE. 2012. Major Rehabilitation of the Jetty System at the Mouth of the Columbia River. Final Report. US Army Corps of Engineers Portland District, Portland, OR. http://cdm16021.contentdm.oclc.org/utils/getfile collection/p16021coll7/id/3/file ame/4.pdf (accessed 9 January 2015).

USACE. 2013. New Jersey Shore Protection, Lower Cape May Meadows – Cape May Point, NJ. Factsheet. US Army Corps of Engineers Philadelphia District Marine Design Center, Philadelphia, PA. http://www.nap.usace.army.mil/Missions/Factsheets/FactSheetArticleView/tabid/4694/Article/6449/new-jersey-shore-protection-lower-cape-may-meadows-cape-may-point-nj.aspx (accessed March 2014).

USACE. 2014. Draft Supplemental Environmental Impact Statement, Mississippi Coastal Improvements Program (MsCIP) Comprehensive Barrier Island Restoration, Hancock, Harrison, and Jackson Counties, Mississippi. US Army Corps of Engineers Mobile District, Mobile, AL. http://www.sam.usace.army.mil/Portals/46/docs/program_management/mscip/docs/MsCIP_DSEIS_02-27-14_Final.pdf (accessed 3 March 2015).

USACE. 2015. Raritan Bay and Sandy Hook Bay Highlands, New Jersey Coastal Storm Risk Management Feasibility Study Draft Integrated Feasibility Report and Environmental Assessment. US Army Corps of Engineers New York District, New York, NY. http://www.nan.usace.army.mil/Portals/37/docs/civilworks/projects/nj/coast/SHtoBIHighlands/Highlands%20Draft%20FR-EA%20Main%20Report.pdf (accessed 11 May 2016).

USACE. 2016. Proposal to Reissue and Modify Nationwide Permits. RIN 0710-AA73. Agency review draft dated 10 February 2016. US Army Corps of Engineers, Washington, DC.

US Department of the Interior (US DOI). 2010. Salazar, Menendez Announce $29 Million to Restore Ellis Island Seawall, Historic Structures under President's Recovery Plan. 26 July 2010. Press Release. US Department of the Interior, Washington, DC. http://www.doi.gov/news/pressreleases/Salazar-Menendez-Announce-29-Million-to-Restore-Ellis-Island-Seawall-Historic-Structures-under-Presidents-Recovery-Plan.cfm (accessed 9 January 2015).

Wasson, K., K. Fenn, and J. S. Pearse. 2005. Habitat differences in marine invasions of central California. Biological Invasions 7:935–948. doi:10.1007/s10530-004-2995-2 (accessed 18 March 2016).

This page intentionally left blank.